91602
new 82-10

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if
Reproduced in Whole or in Part

ontario hydro
research division

To Mr. J.E. Mitchell
Manager
Product Development/Parallel Generation
Market Services and Development Division

INDUSTRIAL LASER REQUIREMENTS FOR AN APPLICATIONS DEMONSTRATION FACILITY

L. Mannik

An assessment is made of the design features of a 1.5 kW carbon dioxide laser that would be suitable for use in a demonstration facility devoted to material processing applications of lasers. Details of laser cutting, drilling, welding and surface treatment are reviewed.

1.0 INTRODUCTION

It is recognized that in order for Ontario industries to remain competitive in the international marketplace, they must keep up with productivity gains achieved by competitors using emerging technologies. In cooperation with Market Services and Development Division, laser material processing has been identified as one area where we lag behind the competition. Over the past decade, high-power lasers have moved from research and development laboratories into the world of manufacturing as their suitability to a wide range of material processing applications has been demonstrated. As a machining tool the laser is capable of cutting, welding, drilling and surface treating both metals and non-metals. In each of these areas it must compete against more established tools and it does this successfully as evidenced by the fact that currently there are over 5,000 lasers used in the US alone to process products worth more than $1 billion per year. However, while Europe and Japan have kept pace with, and in some cases led, these developments,

job	file	date	report no.
16-145-10101	819.35	November 17, 1986	86-289-K

this is not the case in Canada. For example, in the US there are over 50 laser job shops offering machining services in a variety of processing operations, while in Canada there are only two such companies, both of which just started up this year.

One reason for the slow acceptance of this technology is a lack of education of potential users on what lasers can do. Recently there have been signs of progress in this area in the form of workshops organized by Ryerson Polytechnical Institute, Ontario Research Foundation and the National Research Council. However, an even greater stumbling block is the lack of facilities to demonstrate the feasibility of particular applications which may be of interest to specific industries. Plans are underway to correct this by the establishment of an industrial laser applications demonstration facility at Research Division with the support of Market Services and Development Division to encourage the transfer of this technology to the industrial sector, an effort which will also involve staff in the Regions and in Marketing Operations Division to promote this service to potential customers. This report outlines the requirements for a high-power laser which would form the centerpiece of such a facility and describes the applications that this laser would address.

2.0 POTENTIAL APPLICATIONS

The Appendix considers in detail the potential applications of high-power lasers in material processing. Such considerations make it clear that the laser of choice for a broadly-based applications demonstration facility is the carbon dioxide (CO_2) laser, an electrically excited gas laser. The solid state Nd:YAG laser, consisting of a rod of neodymium-doped yttrium aluminum garnet excited by flashlamps, is also used in industrial applications. However, it is more limited in its applicability since it cannot efficiently process non-metals and is not available at powers above 600 W, compared to the CO_2 laser which is commercially available up to 15 kW. The Nd:YAG laser is mainly used in precision hole drilling in the aerospace industry where its smaller focussed spot size is an advantage. A third laser, the excimer, has recently emerged as an industrial tool and has found a niche in semiconductor processing but it is unlikely to supplant either of the two principal types.

The main conclusion that arises from the assessment of potential applications coupled with information on the cost and availability of commercial lasers is that the versatility required for an applications demonstration facility could be achieved with a 1.5 kW CO_2 laser. Such a laser can be expected

to cost at least CAN $200K and would be able to handle a variety of machining operations, including the cutting of 1 cm thick steel and the welding of steel up to a penetration depth of 3 mm.

A fully equipped facility would also have a computer controlled workpiece motion system which can cost as much as the laser, but this is not essential in the initial stages since most of the applications can be demonstrated with a simple laboratory-built moving x-y table.

3.0 CO_2 LASER DESIGN FEATURES

A high-power CO_2 laser basically consists of a water-cooled tube with mirrors on the ends through which a gas mixture of helium, nitrogen and carbon dioxide is flowed and excited electrically. Normally DC excitation is used and the gas flow can be transverse or axial relative to the direction of the output beam. Fast axial flow designs are currently the most popular because they yield high power output in a compact size. However, they also result in higher operating costs because of the increased gas consumption unless a gas recirculation system is included.

RF excitation of CO_2 lasers is an old technology which has been resurrected in the past few years because it offers certain advantages over DC excitation, including stability at high power densities and reduced electrode wear. This means that RF excited lasers can be smaller and lighter and have potentially a much longer service interval (3000 hours vs 1000 hours). Currently only one of the seven major laser manufacturers of CO_2 lasers in the 1.5 kW range features RF excitation but most of the others are seriously evaluating it and within a few years this may turn out to be the industry standard.

It is safe to predict that with a general purpose demonstration facility, there will be potential users who will require more than 1.5 kW for their particular application. With this in mind, the versatility of the facility would be enhanced by a laser with a modular design so that the power could be increased by additions to an existing framework rather than the purchase of a new higher power laser at a much greater cost. One of the manufacturers has come out with such an approach in a laser which can be uprated to 4 kW.

Another feature which is not common but which could prove very useful in a demonstration facility is the ability to vary the energy distribution of the laser output beam in a controlled manner. In many applications a distribution which permits

focussing to the smallest spot size is desirable because this represents the sharpest tool, but in certain situations it would be preferable to have a less tightly focussed beam with a higher power. An example is welding, in which the resulting relaxation in joint fit-up requirements may be an advantage.

Currently most continuous wave (cw) CO_2 lasers can also be pulsed. This provides greater flexibility in the power range covered by the laser since the average power can be reduced by decreasing the pulse repetition rate. Pulsing is also useful in the cutting of thin materials by providing a smaller hole at the start of the cut and by improving the quality of the corners. Pulsing yields peak powers that are two or more times the cw power and this can be advantageous in breaking down the reflectivity of certain metals which impedes many processing applications.

A design feature which is especially desirable in welding applications is power ramping ie. the ability to quickly increase and decrease the output power in a controlled manner. This is essential to eliminating start blow-holes and tail-off crater cracking on almost all welds.

Finally, the question of operating costs also deserves consideration. In some cases the new fast axial flow designs have resulted in factors of 3 to 5 increase in costs, primarily due to increased gas consumption. Designs which recirculate the gas can reduce the gas consumption by a factor of four.

CONCLUSIONS

The following are desirable features of a CO_2 laser to be used in a demonstration facility aimed at a broad spectrum of materials processing applications.

1. A power level of 1.5 kW
2. Fast axial flow design
3. RF excitation
4. Modular design
5. Adjustable energy distribution
6. Pulsing capability
7. Power ramping
8. Low operating costs

RECOMMENDATION

Since no single laser meets all the above requirements, it is recommended that tenders be solicited from the seven major laser manufacturers which offer a majority of these features.

Approved:

A.F. Baljet
Manager
Electrical Research Department

Submitted:

L. Mannik
Research Scientist
Science Section

LM:am

APPENDIX

APPLICATIONS OF HIGH-POWER LASERS IN MATERIAL PROCESSING

A1. Cutting

When a focussed laser beam interacts with the surface of a material, any energy that is not reflected away will be absorbed and thus cause a sudden rise in temperature at the focal point. If the temperature rise is fast enough, which is the case for power densities above $10^5 W/cm^2$, the input heat is capable of vapourizing the material and creating a hole. Relative motion of the laser beam and workpiece then results in cutting.

The cutting action of the laser can be enhanced by the addition of an assist gas which is introduced through a nozzle coaxial to the focussed beam. The high velocity gas jet protects the lens from splatter ejected from the cut zone as well as aiding in material removal by blowing out molten material through the bottom of the cut and, in the case of oxygen, by assisting in the burning process. The enhanced energy density from the use of oxygen rather than air can improve cutting speeds by as much as 40%.

The main advantages of laser cutting are very narrow cut width or kerf, a narrow heat affected zone which minimizes thermal distortion, no tool wear, and the ability to cut materials regardless of their hardness. Thus, CO_2 lasers can cut paper, cloth, wood, metals, ceramics or diamond. Among the few materials that cannot be laser cut because of their high infrared reflectivity are gold and silver, and for the same reason aluminum and copper are more difficult to cut than other metals.

Both the Nd:YAG and CO_2 lasers can be used to cut relatively thin metals of several millimeters thickness. However, if materials with thicknesses in the 10 mm range are to be cut or if higher cutting speeds are desired, only the CO_2 laser can generate the required power. As a point of reference, a 1.5 kW CO_2 laser with oxygen assist is capable of cutting a 10 mm thickness of carbon steel at ~1 m/min, while a 3 mm thickness can be cut at 4.5 m/min. For aluminum, with the same laser power the cutting speed would be a factor of 3 lower and for plastics the same cutting speed could be attained with one third of the laser power.

In laser cutting, the most important performance parameter other than output power is the mode structure of the beam, which determines how sharply the energy can be focussed. The lowest order TEM_{00} mode is one in which the beam profile simulates a

Gaussian distribution so that the radial distribution of energy has only one maximum along the beam axis. Such a mode yields the highest energy density because it can be focussed down to the laser's theoretical minimum spot size, given by the product of the focal length of the lens and the divergence of the beam. Another way of saying this is that the low order mode gives a sharper cutting tool than higher order modes.

Another important laser parameter in determining cut quality is the polarization of the beam. When the direction of polarization is perpendicular to the direction of cutting, the cutting speed is slower, the kerf is wider and the cut appears rougher. To avoid this, lasers for cutting are normally designed with circular polarization so that the effectiveness of cutting is independent of the direction of travel. Other factors which influence cut quality are the stability of the output in terms of power level, mode structure and pointing direction.

While laser cutting is normally performed with cw lasers, pulsed lasers are useful in certain situations such as cutting contours with sharp edges and bends and cutting special materials such as stainless steel. However, pulsing reduces the cutting speed because of the lower duty cycle.

A2. Drilling

Laser drilling is closely related to laser cutting, involving usually slightly higher power densities ($>10^6$ W/cm^2) and similar dwell time or pulse duration (0.1 to 2 ms). Depending on the workpiece material, drilling is accomplished by direct vapourization, melting or a combination of both. Normally pulsed lasers with gas assist are used.

The advantages of laser drilling include high production rate, very small holes (<25 µm diameter), and the ability to drill at low angles to the surface (as low as 10°). Holes can be drilled in the conventional "on-center" method or by trepanning, in which the focussed beam is moved over the workpiece to trace out a hole. This method, which is actually a form of cutting, enables non-circular holes to be drilled down to sizes as small as 0.75 mm.

The shorter wavelength of the Nd:YAG laser (1.06 µm) allows tighter focussing and narrower holes than with the CO_2 laser (10.6 µm). However, some of this advantage is negated by the greater difficulty of achieving the lowest order TEM_{00} mode in high power Nd:YAG lasers. The Nd:YAG laser is preferred for deep hole drilling and for producing holes smaller than 0.75 mm in metals. The CO_2 laser has the advantage of being able to process metals and non-metals.

A3. Welding

Laser welding is performed at lower power densities (10^4 to $5x10^5$ W/cm^2) than cutting or drilling and with longer pulse durations (>2-ms). In most applications of laser welding, energy is transmitted to the material through a process known as keyholing. The concentrated laser energy heats up the material to the point of vapourization which results in the formation of a cylindrical hole called a keyhole. Heat is transferred outward from the keyhole, forming a molten region around the vapour. As the beam moves relative to the workpiece, the molten metal fills in behind the hole and solidifies in a characteristic chevron pattern, forming the weld.

Laser welding is characterized by a high aspect ratio (ratio of penetration depth to melted zone width, typically 8:1), by a narrow heat affected zone resulting in minimal distortion to the workpiece and by strong, porous-free welds.

The laser conditions required for welding are considerably different than those for cutting or drilling where it is only necessary to vapourize and remove the material. With welding it is essential to maintain the metal in the molten phase without producing significant material loss via vapourization. This requires careful control of the power density -- too low results in poor quality, shallow welds while too high produces welds that are porous and unreliable.

CO_2 lasers are the only ones capable of sustaining high enough power outputs to create and maintain a keyhole. Pulsed lasers, including the Nd:YAG laser, are severely limited in their penetration capability and are mainly useful in spot welding applications. All CO_2 laser welding employs an inert shielding gas (argon or helium) to eliminate oxidation embrittlement and porosity produced by the presence of air. In some cases a small amount of oxygen is added to increase the absorption during welding. For example, an increase of up to 100% in weld penetration has been achieved by adding 10% oxygen to the inert gas.

As an indication of the welding capabilities of a 1.5 kW CO_2 laser, for 304 stainless steel a welding speed of 10 mm/s can be attained with a penetration depth of 3 mm and 50 mm/s with a depth of 1 mm. Most steels and zirconium alloys are well suited to CO_2 laser welding while most aluminum alloys are not weldable without the use of a filler material.

The requirement on the fit-up between the two pieces to be welded depends on the focussed spot size which in turn depends on the mode structure of the laser beam. This is the reason that certain welding applications call for a higher order mode,

which relaxes the fit-up requirement, rather than the low order TEM_{00} which is normally the mode of choice. The use of filler material also relaxes the need for a tight fit-up.

A useful laser option in welding applications is power ramping, which allows the laser output power to be varied quickly over a wide range, usually 10-20% to maximum power. This feature is essential in eliminating start blow-holes and tail-off crater cracking that would otherwise result from the instantaneous switching of power on and off the weld.

A4. Surface Treatment

High power lasers are used for a variety of surface processes involving controlled surface layer modification of metals. The advantages of laser surface treatment include conservation of strategic or expensive materials, reduced production costs, increased part life and the use of existing materials in more severe environments. Three of the main processes will be considered here.

A4.1 Hardening

Certain alloys such as carbon steel can be transformed into metastable structures by the application of heat. This structure can be locked in if the rate of cooling is fast enough, resulting in a highly stressed material which is hard and corrosion resistant. The laser has the ability to harden the surface layer of a material without heating up the whole volume and thereby risking distortion of the piece. Laser hardening also requires no external quenchant.

In laser hardening the beam is broadened to avoid energy densities that will melt or vapourize the surface and to maximize surface coverage. Because of its sharply varying energy distribution, the lowest order TEM_{00} mode beam must be defocussed to make it useful in this application. Another approach is to use a higher order mode or a multimode configuration which yields a more even energy distribution and has the added advantage of giving a higher power level. The required power densities (10^3 to 10^4 W/cm^2) are usually obtained with CO_2 lasers of greater than 1 kW. Available power levels with the Nd:YAG laser have limited its use to special cases.

Laser transformation hardening has gained wide acceptance in the automotive industry where it is used on cylinder liners, crankshafts, camshafts, bearings, gears and piston ring grooves to improve hardness, fatigue and wear resistance.

A4.2 Cladding

The objective of cladding, also known as hardfacing, is to fuse an alloy onto the surface of a substrate with minimum dilution of the substrate so that the finished product has an improved ability to withstand harsh environments. Typically an inexpensive substrate is coated with a more expensive alloy that increases the component's wear and corrosion resistance.

While the cladding material can be a wire or a sheet, most commonly it is in the form of a powder which is either placed on the surface or blown onto it during the creation of the laser-generated melt pool. As with other laser-based surface treatments, there is little thermal change to the substrate and relatively slight distortion. Power densities of 10^3 to 10^5 W/cm^2 are normally used for laser cladding.

The automotive and aerospace industries have used this technology for many years and the future looks extremely promising, as indicated by a recent Battelle survey of interest in various aspects of industrial laser processing in which laser cladding for corrosion control came out as the clear winner.

A4.3 Alloying

This process allows the formation of surface alloys with improved corrosion and wear resistance. Small quantities of alloying elements are added as a wire or a powder to a pool of molten metal created by laser irradiation of the substrate. For example, a mild steel part can be surface alloyed with a small amount of chromium to provide the corrosion resistance of stainless steel while conserving an expensive material.

Alloying is a process of controlled dilution and as such it requires a precise control of the energy input, which means that it is nearly impossible to perform surface alloying without a laser as the energy source. Typical power densities are 10^4 to 10^6 W/cm^2 and, as with laser welding, gas shrouding is necessary in most situations. Usually a small keyhole is produced in the substrate and the resulting turbulence promotes mixing of the alloying layer.